AN EVALUATION OF VARIOUS SPACE CLOCKS FOR GPS IIF

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Abstract

This study projects the accuracy of GPS in the Accuracy Improvement Initiative (AII) environment given current satellite clocks and the future Block IIF cesium and rubidium clocks. AII is an upgrade to the GPS control segment that incorporates additional tracking stations and replaces the current partitioned filter with a fully correlated one. Real data, obtained during two weeks of October 1998, were modified when appropriate for simulated clocks. A simulation of the AII estimator is exercised on these data and its states used to predict user navigation messages, which are then compared to a truth reference. It is concluded that the IIF satellites, using either their cesium or rubidium clocks, would meet the AII accuracy specification assuming one upload per satellite per 6 hours, but that the Block IIA satellites with their cesium clocks would not. An upload rate of once per day is possible only with the IIF Rb clock. Suggestions are made for improving estimator performance.

INTRODUCTION

Space clocks used for GPS II were first built using technology from the late 70's and early 80's. These rubidium (Rb) and cesium (Cs) clocks generally operated for less than their life expectancy, but never contributed directly to the loss of any satellite. Different clock configurations were used for GPS II, starting with two Rb clocks and two Cs clocks for the Block II/IIA. Later for Block IIR, a two Rb and one Cs configuration was planned for each satellite. However, a final configuration of three Rb was used instead to keep the program on schedule. On-orbit testing of these Rb clocks by the Naval Research Laboratory indicated that they performed much better than specification.

Wu and Feess [1] estimated the IIF range error contributions from random clock noise using the clocks' measured Allan Deviation for Rb clock, built by Perkin Elmer, and digital Cs clock, built by Datum-Beverly. They compared their assessment against the Operational Requirements Documents (ORD) threshold range requirements. They also evaluated the GPS signal-in-space (SIS) User Range Error (URE), which include all the space and control segments errors, for IIF Rb and Cs clocks for up to 3-hour age of data (AOD), the maximum AOD assuming Navigation Message Update (NMU) is operational. The objective of this study is to extend their evaluation of the GPS accuracy to a 24-hour period, given the performance characteristics of the three GPS clocks presented in [1]. This yields the sensitivity of SIS performance to upload rate. The evaluation examines the impact of clock error characteristics on predicted SIS URE as compared to the 1999 GPS ORD, which calls for a threshold ranging accuracy of 1.5 m and an objective of 0.5m [2].

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APPROACH

Real 15-minute measurements to the five GPS Operational Control Segment (OCS) stations and six National Imagery and Mapping Agency (NIMA) stations taken during 2 weeks of October 1998 were used. These data were modified as necessary by replacing the measurement domain impact of NIMA estimate of actual on-board clocks with that of clocks simulated to have the error characteristics of the clocks of [1]. The modified measurements were input to a simulation of the AII estimator whose states were then used to generate predictions corresponding to user navigation message uploads. Fresh uploads are generated whenever the maximum AOD is reached. The predictions are compared to NIMA best-fit ephemeris and the NIMA or simulated clocks and error statistics are computed.

The SIS URE is a performance measure of GPS user message accuracy. For this study, we use the SIS URE formula as provided by [3] and defined as

$$SIS\_URE = \sqrt{(\Delta R - \Delta C)^2 + 0.0192(\Delta IT^2 + \Delta CT^2)} \tag{1}$$

where ΔR, ΔIT, and ΔCT are ephemeris errors in radial, in-track, and cross-track respectively, and ΔC is the clock error (note that the mean of (ΔR-ΔC) has been removed). The SIS URE for this study is defined as the rms value of the total Space/Control segment. It is one of the two components that make up the ORD range error. The other is the User Equipment Error (UEE), which is defined as the rms value of the total User segment range error. The total statistical User Equivalent Range Error (UERE) is then defined as

$$UERE = \sqrt{SIS\_URE^2 + UEE^2}\,. \tag{2}$$

Based on the threshold range error of 1.5 m UERE in the 1999 ORD, the range error contribution from the SIS URE can be as much as 1.25 m if the error from UEE is kept at 0.8 m or less.

RESULTS AND ANALYSIS

The various resulting SIS UREs as a function of time (i.e., the root-mean-square or rms of the entire GPS constellation) for the three clock cases are shown in Figures 1a, 1b, and 1c, for a 2-week GPS tracking period in October 1998. The SIS URE for a perfect clock (PC) case is also shown in these figures for comparison. Figure 1a depicts the projected total SIS URE for all the cases. As evidenced from the figure, IIF Rb and PC URE are approximately 0.5 m for up to 5 hours AOD, suggesting that they will support the 1999 ORD objective range accuracy, provided the AOD is 5 hours or less. The two Cs cases, however, already have SIS URE that are larger than 0.5 m. From 6 hours AOD onward, the SIS URE for PC, IIF Rb, and IIF Cs are still within 1.5 m, but the SIS URE for the II/IIA CS case rises to more than 2.5 m. Figure 1b shows clock message error statistics. It is interesting to note that the curves for IIF Rb and IIF Cs compare very closely to those generated using only the clock's measured Allan variance from engineering and production units as reported by Wu and Feess [1] (see Figure 2). This indicates that clock estimation error does not significantly contribute to SIS URE. Ephemeris message error statistics were plotted in Figure 1c. We observe that the IIF Rb and PC cases are essentially identical, suggesting that clock improvement beyond IIF Rb will not be helpful. For consistency with the study in [1], the results obtained here did not involve tuning of the Kalman filter. Suggested ephemeris estimation/prediction improvements can be found in [1], and are summarized here for completeness. They are: retuning the Kalman filter, improving the atmospheric modeling and multi-path mitigation, and estimating parameters not currently modeled in the filter.

The current Block IIF baseline is to operate using the Navigation Message Update with a minimum update rate of once every 3 hours. Based on their study, Wu and Feess [1] concluded that the SIS URE for IIF Rb and Cs with 3 hours AOD can readily support the 1999 ORD range threshold of 1.5 m with today's user equipment technology. On the other hand, if the 3-hour update rate cannot be achieved, this study shows that IIF Rb and Cs clocks can still support the 1999 ORD threshold range accuracy with an update rate of once every 6 hours using today's user equipment technology. In this case, the UEE component is 1.38 m and 1.24 m for Rb and Cs respectively. For an update rate of twice a day or less, the allocable UEE for IIF Cs is 1.0 m or less, a stringent requirement for today's equipment. Thus, only IIF Rb clock can support the ORD range threshold accuracy for up to 24 hours AOD. This is because the SIS URE of IIF Rb at 24 hours AOD is 0.75 m, yielding the UEE of 1.29 m using Equation (2), which is possible for current equipment technology.

It is also interesting to look at the SIS URE in a different way, specifically, by plotting the SIS URE as a function of Space Vehicle (SV). For brevity, we show only an example of the total URE, as well as URE due to each of clock and ephemeris, for the 3-hour AOD, IIF Rb case in Figure 3. The beneficial correlation of radial and clock errors results in the total SIS URE being significantly less than the root-sum-square (rss) of its clock and ephemeris contributions. This good correlation exists only for the 3- and 6-hour AOD for all the clock cases. Beyond the 6-hour AOD, the correlation is less noticeable, as shown in Figure 4 for a 12-hour AOD IIF Rb case.

SUMMARY

This study examines the SIS URE of GPS Block IIF for three different clocks. With the current operations baseline, it is concluded both IIF Rb and Cs clocks can support the 1999 ORD threshold range accuracy. However, if a situation arises where there are no more than two uploads per day, the analysis here indicates that only IIF Rb can support the ORD threshold accuracy with today's user equipment technology.

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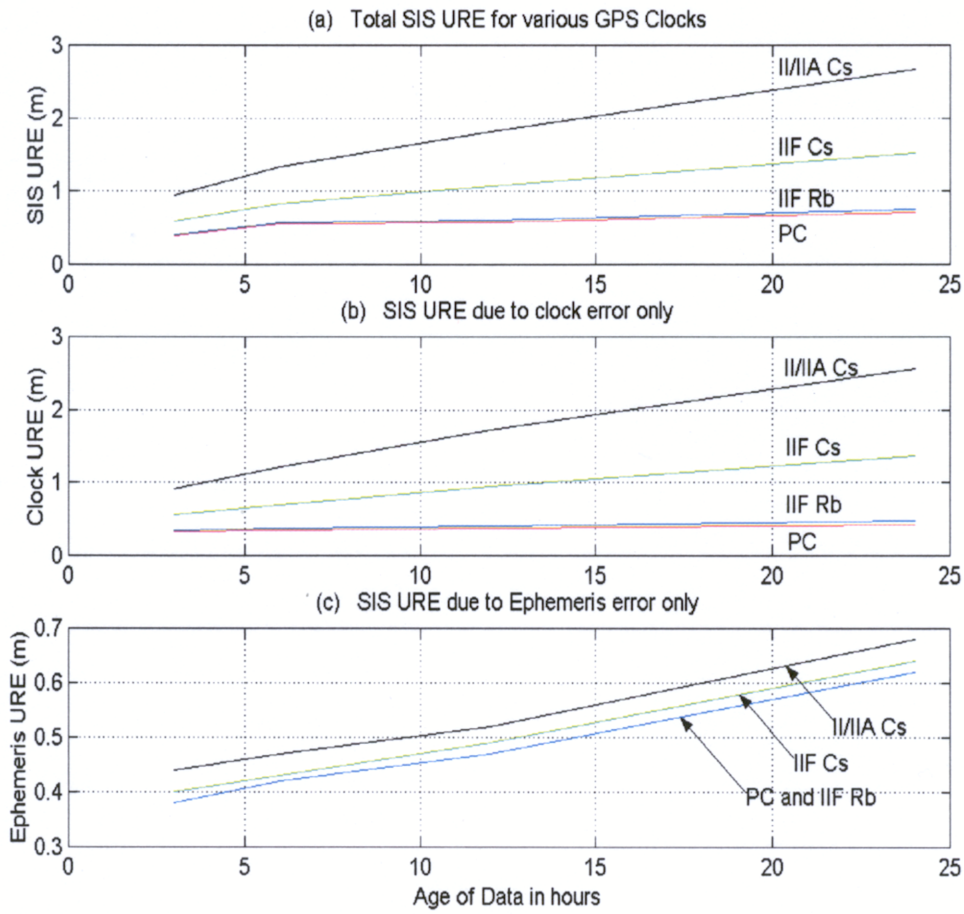

Figure 1. Various SIS URE as a function of time for different GPS clocks, for a 2-week period in Oct 1998. (a) Total SIS URE, (b) SIS URE due to clock error only, and (c) SIS URE due to ephemeris error.

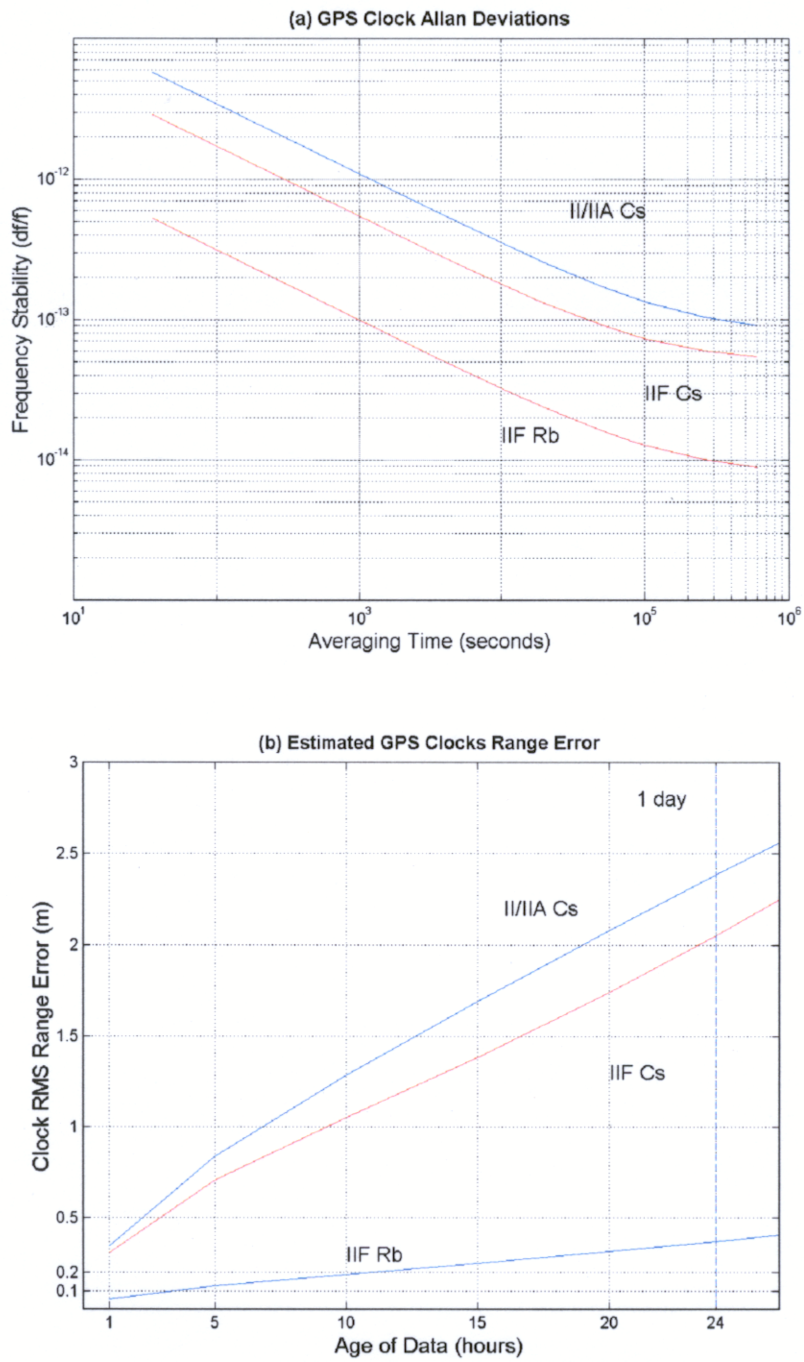

Figure 2. (a) Allan variances of GPS Block IIF, and (b) estimated IIF clocks Range Error.

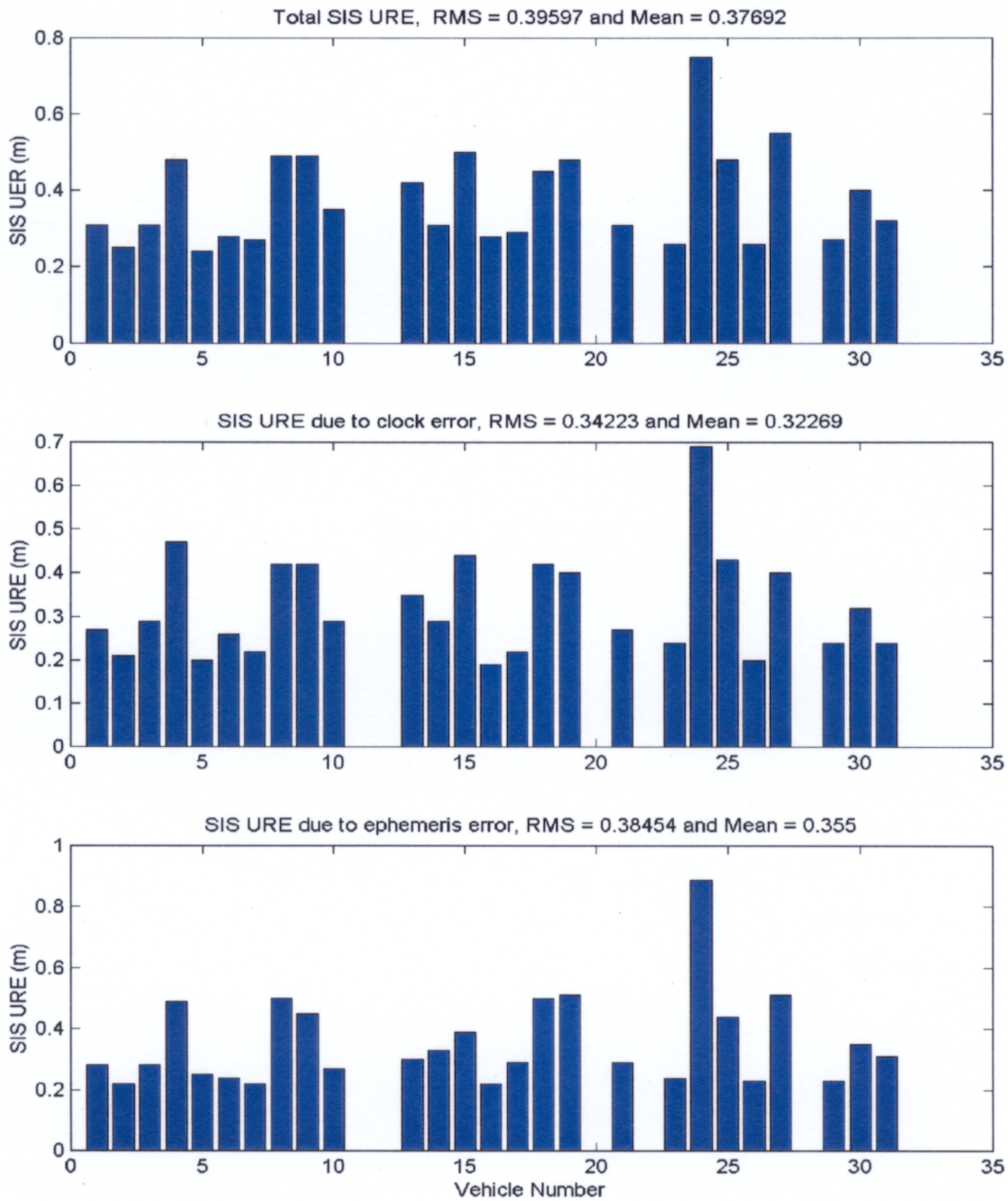

Figure 3. SIS URE for 3-hour upload for a Rb clock. There is high correlation between ephemeris and clock for a 3-hour age of data scenario. Note that the total SIS URE is much lower than the rss of the components.

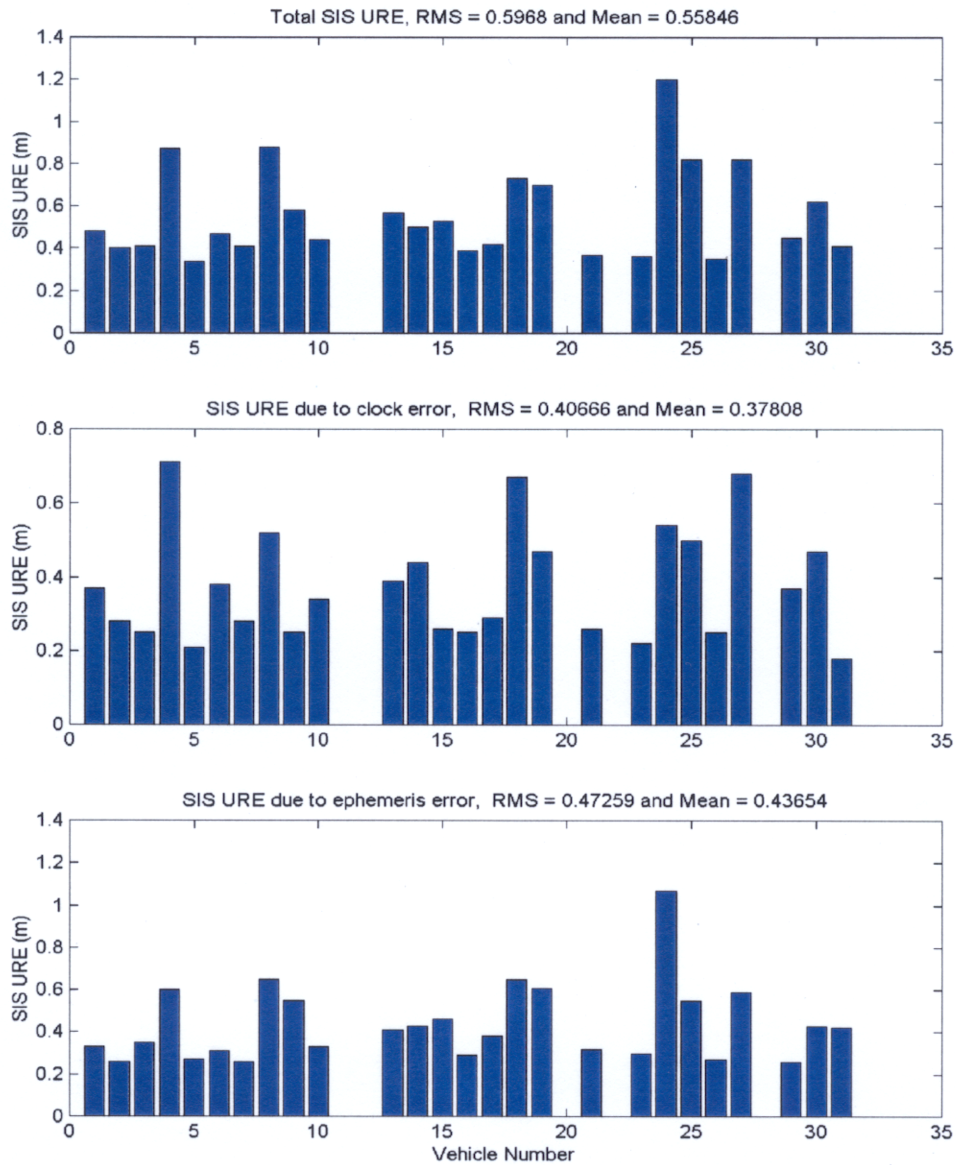

Figure 4. SIS URE for 12-hour upload for a Rb clock. In contrast to the 3-hour case, the 12-hour case illustrates a lower correlation between clock and ephemeris SIS URE.